Authenticating Pollock Paintings Using Fractal Geometry

R. P. Taylor,[a,*] R. Guzman,[a] T.P. Martin,[a] G.D.R. Hall,[a] A.P. Micolich,[b] D. Jonas [b] and C.A. Marlow[a]

[a] Physics Department, University of Oregon, Eugene, OR 97403, USA

[b] School of Physics, University of New South Wales, 2052, Australia

[*] Corresponding author: rpt@darkwing.uoregon.edu
phone: 1-541-346-4741, fax: 1-541-346-5861

Jackson Pollock's paintings are currently valued up to US$40M, triggering discussions that attributation procedures featuring subjective visual assessments should be complimented by quantitative scientific procedures. We present a fractal analysis of Pollock's patterns and discuss its potential for authenticity research.

Key Words: Abstract art, Jackson Pollock, authenticity, fractals

1. Introduction

In March 1952, Jackson Pollock (1912-1956) laid down the foundations of his masterpiece *Blue Poles: Number 11, 1952* by rolling a large canvas across his studio floor and dripping fluid paint from an old can with a wooden stick (Varnedoe, 1998). The painting, shown in Figure 1, represents the culmination of ten years of development of his "pouring" technique. In contrast to the broken lines painted by conventional brush contact with the canvas surface, Pollock poured a constant stream of paint onto his horizontal canvases to produce continuous trajectories. Twenty years later, when the painting sold for US$2M, only works by Rembrandt, Velázquez and da Vinci commanded higher prices. Pollock's works continue to grab attention, as witnessed by the success of the retrospectives during 1998-99 when prices of US$40M were discussed for *Blue Poles*: *Number 11, 1952*. As the commercial worth of Pollock's paintings continue to soar, judgments of authenticity have become increasingly critical. If a poured painting of unknown origin is found, such as the one shown in Figure 2, what methods should be employed to decide if it is a long-lost masterpiece or a fake? When dealing with such staggering commercial considerations, subjective judgments attempting to identify what art scholars call the 'hand' of the artist - the tell tail visual trademarks - may no longer be fully adequate. In particular, subjective judgments have become increasingly difficult to defend against potential litigation (Spenser, 2004). What is becoming clear is that subjective assessments should be coupled with more quantitative and objective scientific investigations.

Unification of artistic and scientific investigations is not a new proposal for authenticity research. Investigations of paintings of unknown origin often call on a diverse range of consultants. From the arts, provenance studies (where an art historian judges the painting's history relative to known facts about the artist) are coupled with connoisseurship (where an art expert compares a visual inspection of the painting with the catalog of known paintings). From the sciences, a range of techniques can be employed to date or determine the material composition of the paint, canvas and frame (Coddington, 1999; McCrone, 2001; Spenser, 2004). For many artists, this combination of research tools yields compelling evidence for attributing paintings. Unfortunately, Pollock's unique history adds uncertainty to these studies. For example, financial success arrived late in his life, forcing him to barter paintings (Naifeh and Smith, 1989; Potter, 1985). These casual, unrecorded exchanges of paintings create a challenge for provenance judgments – long-lost Pollock paintings may exist where a clear historical link between the artist and the current owner is beyond trace. Furthermore, Pollock was the subject of unprecedented publicity at his peak, including a film documentary (Namuth, 1980) that exposed his pouring technique to the public. The resulting wave of Pollock imitators is well-documented and provides proof of the existence of non-Pollock poured paintings dating from Pollock's era and composed using similar paints and canvases. This limits scientific techniques that aim to distinguish paintings based on material composition and age. These complications emphasize the importance of scientific pattern analysis for authenticity research.

In this Letter, we build on our earlier computer analysis of 5 Pollock paintings that showed his poured trajectories to be composed of fractal patterns (Taylor et al., 1999a, 1999b). We previously described his style as 'Fractal Expressionism' to distinguish it from computer-generated fractal art (Taylor et al., 1999b). Fractal Expressionism indicates an ability to generate and manipulate fractal patterns *directly*. The discovery raised a critical question that triggered considerable debate: how did Pollock manage to paint such intricate fractal patterns, so precisely, and do so twenty-five years head of their scientific discovery in Nature? Some art scholars interpreted these achievements in terms of remarkable artistic talent, while others proposed that fractals are perhaps an inevitable consequence of pouring paint. Here we present evidence showing that fractals arise from the specific pouring technique developed by Pollock. We consider whether this ability is unique to Pollock and explore the potential of fractal analysis techniques as an authenticity tool. First, we analyze 17 paintings, selected from Pollock's catalog to represent the variety of his poured work, and identify a precise and highly distinguishable set of fractal characteristics shared by *all* the paintings. Secondly, we analyze 37 poured paintings generated by students and also 14 poured paintings of unknown origin (submitted by private collectors in the USA who believe the paintings to date from the Pollock era), and show that *none* of these paintings exhibit the set of fractal characteristics identified in Pollock's paintings. We discuss the implications of these results for authenticity research and consider the extent to which this fractal analysis might be extended to abstract and figurative paintings by other artists.

2.1 Fractal Analysis of Pollock Paintings

What is the identifying 'hand' of Pollock? His poured patterns stand in sharp contrast to the straight lines, triangles and the wide range of other artificial shapes belonging to Euclidean geometry. Instead, his poured paintings are frequently described as 'organic' (Potter, 1985), suggesting that they allude to Nature. Since its introduction in the 1970s, fractal geometry has experienced remarkable success in describing the underlying patterns of many of nature's objects, including coastlines, clouds, flames, lightning, trees and mountain profiles (Barnsley, 1992; Gouyet, 1996; Mandelbrot, 1977). In contrast to the smoothness of Euclidean shapes, fractals consist of patterns that recur on finer and finer magnifications, building up shapes of immense complexity. Given the 'organic' appearance of Pollock's paintings, the first step towards identifying the 'hand' of Pollock is to adopt the pattern analysis techniques used to identify fractals in Nature's scenery and apply the same process to his canvases. Nature's fractals obey statistical self-similarity - the patterns observed at different magnifications, although not identical, are described by the same spatial statistics (Mandelbrot, 1977). To detect statistical self-similarity, a scanned photographic image of the painting is covered with a computer-generated mesh of identical squares. By analyzing which of the squares are 'occupied' (i.e. contains a part of the painted pattern) and which are 'empty', the statistical qualities of the pattern can be calculated. Reducing the square size in the mesh is equivalent to looking at the pattern at a finer magnification. Thus, in this way, the painting's statistical qualities can be compared at different magnifications.

As an example, we consider the analysis of *Blue Poles*: *Number 11, 1952* (actual size 210.4cm by 486.8cm), for which we use a 42.0cm by 97.4cm high-resolution photographic print of the painting as the source image. Our current analysis procedures employ an HP Designjet 815mfp scanner, which allows such an image to be scanned using a one step process. We note, however, for the results reported in this Letter, the scanner's window size was limited to 42.0cm by 42.0cm, necessitating a two-step procedure as follows. First, a 42.0cm by 42.0cm section of the print was scanned at 1200dpi, creating a 24bit color bitmap image with 19842 pixels across each length. The analysis of this image examines pattern sizes ranging from the smallest speck of paint (0.8mm on the canvas) up to sizes matching the height of the canvas (210.4cm). Within this size range, the analysis is not affected by any image resolution limits, such as those associated with the photographic or scanning procedures. For example, the pixel separation after scanning corresponds to a physical size of 0.1mm on the canvas, and thus the smallest painted pattern spans 8 pixels. Similarly, the graininess associated with the photographic process corresponds to the order of several pixels. A visual inspection confirms that the smallest analyzed pattern is undistorted. To analyze patterns across size scales larger than the canvas height of 210.4cm, including those spanning the entire canvas length of 486.8cm, a smaller photographic print (18.1cm by 42.0cm) was required in order to fit the painting's full image within the length of the scanner window (42.0cm). By combining the two sets of analysis, we find that the largest observed fractal pattern is over one thousand times larger than the smallest pattern (see below) (Taylor et al., 1999a, 1999b). This size range is significantly larger than for typical observations of fractals in other physical systems (where the largest patterns are typically just twenty-five times larger than the smallest pattern) (Avnir et al., 1998). A consequence of observing the fractal patterns over such a large size range is that parameters that characterize the fractal statistics can be determined with accuracy.

2.2 Fractal Dimensions of Pollock Paintings

A crucial parameter for characterizing a fractal pattern is the fractal dimension, D, and this quantifies the scaling relationship between the patterns observed at different magnifications (Mandelbrot, 1977). For Euclidean shapes, dimension is a simple concept and is described by the familiar integer values. For a smooth line (containing no fractal structure) D has a value of 1, while for a completely filled area its value is 2. However, the repeating structure of a fractal line generates a non-integer D value that lies in the range between 1 and 2 (Schroeder, 1991). A fractal pattern's *D* value can be determined by applying the well-established "box-counting" technique (Gouyet, 1996) to the computer-generated mesh of squares discussed above. Specifically, if *N*, the number of occupied squares (or "boxes"), is counted as a function of *L*, the square size, then for fractal behavior $N(L)$ scales according to the power law relationship $N(L) \sim L^{-D}$ (Gouyet, 1996; Mandelbrot, 1977). This power law generates the scale invariant properties that are central to fractal geometry. The *D* value, which charts this scale invariance, can be extracted from the gradient of the 'scaling plot' of log(*N*) plotted against log(*L*). The standard deviation associated with fitting the data to the fractal scaling behavior is such that *D* can be determined to an accuracy of 2 decimal places. The *D* value can be confirmed using a derivative analysis of the scaling plots (Taylor, 2002).

We adopt two commonly used magnification procedures to construct the scaling plots and find them to be consistent. For the first procedure, the square size *L* is reduced iteratively using the inverse expression $L = H/n$, where *H* is the canvas size and *n* is the number of iterations ($n = 1, 2, 3 \ldots$). For the second procedure, the exponential expression $L = H\,C^{-n}$ (where *C* is a selected magnification factor) is applied iteratively. The first procedure has the advantage of generating a larger number of data points, while the second procedure reduces computation time and produces equally spaced points across the resulting log-log scaling plot. For both procedures, the validity of the counting procedure increases as *L* becomes smaller and the total number of boxes in the mesh is large enough to provide reliable counting statistics (Gouyet, 1996). In typical scaling plots of Pollock's canvases, the large number of boxes in the mesh ensures reliable counting statistics across the entire range of analyzed size scales. Consider, for example, the mesh of squares covering the full image of *Blue Poles: Number 11, 1952*. For the finest length scales analyzed (corresponding to the smallest, resolvable pattern size on the canvas of L = 0.8mm) there are 16 million boxes in the mesh. The coarsest length scale analyzed is set to ensure that the number of boxes doesn't become too limited at large *L* values. For *Blue Poles: Number 11, 1952*, this is set at L = 30cm, which corresponds to approximately one sixteenth of the canvas length and 112 boxes in the mesh. We note, however, that for some paintings well-defined fractal scaling behavior has been observed up to *L* values corresponding to 50 boxes in the mesh before significant scatter emerges in the scaling plot data.

To confirm the reliability of the whole (scanning and analysis) procedure, we generate a set of computer-generated test patterns, including Euclidean and fractal shapes. These test patterns are printed at a resolution matching the source image of the paintings, and then scanned and analyzed using the procedure outlined above. A comparison of the measured *D* values with the known values for these test patterns confirms the accuracy of the procedure. To date, we have employed the procedure to analyze 17 Pollock paintings: *Composition with Pouring 11* (1943), *Water Birds* (1943), *Untitled* (1945), *Free Form* (1946), *Lucifer* (1947), *Full Fathom Five* (1947), *Number 14, 1948* (1948), *Figure* (1948), *Number 23, 1948* (1948), *Number 8, 1949* (1949), *Number 27, 1950* (1950), *Number 32, 1950* (1950), *Autumn Rhythm: Number 30* (1950), *Unknown* (1950), *Untitled* (1951), *Blue Poles: Number 11, 1952* (1952) and *Convergence: Number 10, 1952* (1952). Independent analysis performed subsequently by others (Mukeika et al., 2004) has confirmed the fractal character of *Full Fathom Five* (1947), *Autumn Rhythm: Number 30, 1950* (1950) and *Blue Poles*: *Number 11, 1952* (1950), along with six additional Pollock paintings: *Reflections of the Big Dipper* (1947), *Number 1A, 1948* (1948), *Number 1, 1949* (1949), *Number 28, 1950* (1950), *Number 31* , 1950 (1950), and *Lavender Mist: Number 1, 1950* (1950). This collection of 23 Pollock paintings spans the full variety of Pollock's poured painting catalog: from his first attempts of 1943 up to his final, mature works of 1952, from one of his smallest paintings (48.9 by 35.5 cm of *Free Form*) to one of his largest canvases (266.7 by 525.8cm of *Autumn Rhythm: Number 30, 1950*), and paintings created using different paint media (enamel, aluminum, oil, ink and gouache) and supports (canvas, cardboard, paper and glass).

The scaling plot resulting from the box-counting analysis performed on *Blue Poles: Number 11, 1952* is shown in Figure 3(a). The plot of *N* against *L*, on log-log (base 10) axes, is generated using the magnification expression $L = H\,C^{-n}$ (where $C = 1.1$ and $H = 1052$mm). This produces 54 data points in the range of *L* shown, compared to over 1000 points generated from the equivalent inverse expression $L = H/n$ (Taylor et al., 1999b). For small sizes the scaling plot follows one straight line (and hence one *D* value) and then crosses over to another straight line of a different gradient at the transition size marked L_T. We note that this multi-fractal behavior, for which the scaling plots are characterized by two distinct scaling regimes, is expected from the studies of the physical processes used by Pollock (to be discussed in Section 2.4) and is also observed in certain natural fractals (in particular, tree forms). We label the dimensions extracted from the two gradients the drip fractal dimension, D_D, and the Lévy fractal dimension, D_L (see below for an explanation of nomenclature). An iterative fitting procedure uses D_D, D_L and L_T as adjustable parameters to minimize the standard deviation, *sd*, of the data from the two linear fit lines. For the fit shown in Figure 3(a), the values of D_D = 1.63, D_L = 1.96 and L_T = 1.8cm produce *sd* = 0.020. At larger scales, approaching $L \sim$ 50cm-100cm (the size depends on the painting), the painting 'space fills' (i.e. all the boxes in the mesh are occupied) and, as a consequence, the gradient shifts to $D = 2$. For paintings with low D_L values this second transition to $D = 2$ is clear in the scaling plots. This is not the case for paintings with high D_L values (as is the case for Figure 3(b)), and the transition length is instead determined by examining the box size below which empty boxes start to occur.

2.3 De-construction of Pollock Paintings

Many of Pollock's paintings feature a number of different colored layers of paint. These paintings are electronically deconstructed into their constituent colored layers and a box-counting analysis is performed on each layer. For example, for *Blue Poles: Number 11, 1952*, 5 layers were extracted for analysis (blue-black, aluminum, light yellow, dark yellow and orange) and Figure 3(a) shows the box-counting analysis of the aluminum layer. The color separation is performed by identifying the RGB range (on a scale of 0 to 255 for each of the red, green and blue channels) of the color variations within each layer and then filtering accordingly. For these multi-colored paintings, we emphasize that the layers are interactive in character - as the trajectories of one layer were deposited they obscured parts of the underlying layers' patterns. The analyzed patterns therefore correspond to those seen by the observer of the complete painting rather than the patterns as they were deposited. Of the 17 paintings listed above, 14 are multi-layer paintings (a proportion that is approximately representative of Pollock's catalog of poured paintings). In total, 35 colored layers have been extracted from the 17 paintings, and the box-counting analysis confirms that each of these constituent layers is fractal with well-defined D_D, D_L and L_T values. The *sd* values of the fits lie in the range $0.009 < sd < 0.025$, with a mean value of 0.019 and a standard deviation from this mean of 0.004. We note that *sd* decreases with canvas size: for example, the average *sd* value for the layers of *Autumn Rhythm: Number 30, 1950* (canvas area of 140,200cm^2) is 0.020, compared to 0.010 for *Number 23, 1948* (canvas area of 4,508cm^2).

Having separated the component colored layers and shown each to be fractal, the painting is then 're-constructed' by re-incorporating the layers to build the complete pattern. As each of the colored layers is re-incorporated, the two fractal dimensions, D_D and D_L, of the overall painting rise (Taylor, 2000, 2003a). Thus the combined pattern of many colors has higher fractal dimensions than any of the single layer colors. For example, the fractal dimensions of the aluminum layer of *Blue Poles*: *Number 11, 1952* are D_D = 1.63 and D_L = 1.96, compared to the higher values of D_D = 1.72 and D_L = 2 for the complete painting. The D_D value of the complete painting is a particularly sensitive parameter for investigating the poured paintings. By analyzing Pollock's poured paintings over a decade (from 1943 to 1952) we can use D_D to quantify the evolution in his fractal patterns, as shown in Figure 4. Art theorists categorize the evolution of Pollock's pouring technique into three phases (Varnedoe, 1998). In the 'preliminary' phase of 1943-45, his initial efforts are characterized by low D_D values. An example is the fractal pattern of the painting *Untitled* from 1945, which has a D_D value of 1.12. During his 'transitional phase' from 1945-1947, he started to experiment with the pouring technique and his D_D values rose sharply (as indicated by the first gradient in Figure 4). In his 'classic' period of 1948-52, he perfected his technique and D_D rose more gradually (second gradient in Figure 4) to the value of D_D = 1.7. An example is *Autumn Rhythm: Number 30, 1950*. During his classic period he also painted *Untitled*, which has an even higher D_D value of 1.89. However, he immediately erased this pattern (it was painted on glass), prompting the speculation that he regarded this painting as too complex and immediately scaled back to paintings with D_D = 1.7. This suggests that his ten years of refining the pouring technique were motivated by a desire to generate fractal patterns with $D_D \sim 1.7$. We note the potential use of the graph shown in Figure 4 for establishing an approximate date for authentic Pollock paintings.

2.4 The Fractal Generation Process

Having identified the precise fractal characteristics of Pollock’s paintings, we now address whether these characteristics and the processes that generated them are unique to Pollock. Our previous fractal analysis of the film and photographs of Pollock (recording the evolution of his paintings at different stages of completion) reveals a remarkably systematic process (Taylor et al., 2003b). He started by painting localized islands of trajectories (approximately 50-100cm in size) distributed across the canvas, followed by longer extended trajectories that joined the islands, submerging them in a dense fractal web of paint. This process was swift with the fractal dimensions of the painting rising sharply in a time frame of several minutes (Taylor et al., 2003b). Over an extended period of time (6 months in the case of *Blue Poles*: *Number 11, 1952*), he would then deposit the extra layers of different colored paint on top of this initial ‘anchor’ layer. During this final stage he appeared to be fine-tuning the D values, with values rising by less than 0.05. This deliberate, refined process raises the possibility that fractals are not an inevitable consequence of pouring paint but are instead the result of Pollock's specific pouring technique (Taylor et al., 2003b).

This speculation is supported by an analysis of the physical processes used by Pollock to generate the two sets of fractal patterns described by D_D and D_L. Studies of the film and still photography (Taylor et al., 1999b; Taylor, 2000, 2003a) show that the small scale patterns quantified by D_D were predominantly generated by the pouring process – the dynamics of the fluid paint as it fell though the air and interacted with the canvas. The larger scale patterns described by D_L were predominantly shaped by Pollock's motion. The potential of these two processes to generate fractals depends critically on parameters relating to Pollock's painting technique (Taylor et al., 1999b; Taylor, 2000, 2003a). It is well-established that falling fluid can decompose into a sequence of fractal droplets (Shi et al., 1994). In Pollock's case, formation of fractal droplets would depend on the paint viscosity and the manner in which he 'launched' the paint from his painting implement. If, for example, the paint was too fluid, or the drop distance was too short, then fractal drops would not form. Similarly, fractals permeate human motion only under specific conditions. Our preliminary research indicates that human motion follows fractal 'Lévy flights' (Taylor, 2004) when people restore their balance (Taylor et al., manuscript in preparation). This suggests that perhaps Pollock's motions were performed in a state of controlled "off-balance", and that he deliberately tuned into the fractal behavior of this underlying physiological process. This motion produced fractal trajectories that linked together the islands in the underlying anchor layer. In general, Pollock didn't paint trajectories longer than the island size of approximately 100cm, and consequently at larger scales the painting is non-fractal with $D = 2$.

In summary, the emerging science of his painting process predicts that it is possible to generate both fractal and non-fractal patterns, depending on the parameter conditions chosen by the artist. This is confirmed by our analysis of the patterns of paint found on Pollock's studio floor. These patterns, created by the paint that missed the canvas, are not fractal, emphasizing that Pollock's fractals were a direct consequence of the way that he aimed the paint at the canvas - the fractals were a product of Pollock's compositional technique. The concept that poured paintings can either be fractal or non-fractal is further supported by our studies in which a chaotic pendulum was employed to pour paint onto a horizontal canvas (Taylor, 1998, 2003a). When the chaos in the swinging motion was suppressed, the resulting poured paintings were devoid of fractal content (Taylor, 2002).

2.5 Fractal Analysis of Poured Paintings not Attributed to Pollock

Fractal patterns are therefore the product of the specific technique Pollock used to pour paint and all of the analyzed poured paintings have this fractal composition. In fact, the 'hand' of Pollock is more specific than fractality – through our empirical study, we can identify trademark features of Pollock's fractal patterns common to all of the analyzed Pollock paintings. These trademarks combine to have a profound impact on the visual character of his work and are summarized as follows: (1) Pollock paintings are composed of two sets of fractal patterns (generated by the pouring process and his Lévy motions), (2) these fractal patterns occur over distinct length scales. In particular, although the transitional length scale L_T varies between Pollock paintings (depending on factors such as canvas size), L_T always lies within a specific size range of several centimeters (in order to protect the potential of this procedure for authenticity research, the precise range of L_T values observed for authentic Pollock paintings remains confidential), (3) each set of fractal patterns is well-described by a fractal dimension extracted from the gradient of the log-log scaling plot, (4) the condition $D_L > D_D$ is always satisfied (the exact relationship between D_L and D_D remains confidential for the above reasons), (5) if the painting is composed of a number of colored layers, each layer satisfies the previous 4 criteria, (6) the quality of the fits of the scaling plot data to the above characteristics is quantified by *sd* values that never exceed 0.025, with lower *sd* values down to 0.009 measured for the smallest paintings.

To examine the extent to which this set of fractal characteristics is unique to Pollock, 37 undergraduate students from the University of Oregon were asked to generate abstract paintings using the pouring technique. The painting parameters were chosen to match Pollock's more simple, black and white poured paintings such as *Number 23, 1948* (57.5cm by 78.4cm). The students were asked to paint a single black layer on an area measuring 61.6cm by 91.5cm. The box-counting analysis revealed that *none* of the 37 paintings matched all 6 of the required criteria. In the attempt to match to the criteria, the computer fits the scaling plot data to two straight lines (one for low L values and the other for high values), as required by criterion 1. This fitting procedure uses the L_T value as a free variable to minimize the standard deviation of the fit lines to the data. If the L_T value obtained by the fitting procedure lies within the accepted size range (criterion 2), then the other criteria are assessed. If the L_T value fails to lie within the required range, the painting is given a "second chance", for which the fitting procedure is repeated using L_T = 3.0cm (the average L_T value for all analyzed Pollock paintings). Using this "forced fit", the remaining criteria are then assessed. All of the 37 paintings required the forced fit procedure. An example painting (labeled *Dripfest35*) is shown in Figure 5. Despite any superficial similarities with Pollock's work, this painting does not match the required 6 criteria listed above. The "forced-fit" analysis is shown in Figure 3(b). To facilitate a comparison of quality of fit between the paintings produced by Pollock and the students, the fitting procedure is assessed over a common magnification range of 1mm < L < 10cm and uses the same magnification factor (C = 1.1) to ensure an identical number of data points across this range of L. For the fit shown in Figure 3(b), sd = 0.053, compared to 0.010 for Pollock's equivalent *Number 23, 1948*. For the 37 paintings, the sd values of the fits fall outside the range observed for Pollock paintings. Their sd values are the range 0.030 < sd < 0.053, with a mean value of 0.037 and a standard deviation from this mean of 0.006.

For poured paintings of unknown origin, it is informative to perform a fractal analysis to determine if the above criteria are satisfied. To date, we have analyzed 14 poured paintings supplied to us by private collectors. *None* of these paintings matched the required 6 criteria. Out of the 49 layers extracted from the 14 paintings, 18 used the 'free-fit' procedure. An example is the black layer of the painting shown in Figure 2 (labeled *Unknown12*). The painting's scaling plot is shown in Figure 3(c) and the fit is quantified by sd = 0.038. For the 14 paintings, the sd values lie in the range of 0.031 < sd < 0.072. We note that the larger sd values exhibited by both the student paintings and the paintings of unknown origin quantify clear deviations from the established Pollock fractal characteristics (ie the 6 criteria). These deviations are clearly evident in all of the scaling plots – as demonstrated, for example, in Figure 3(b, c). The manner in which the data deviates from Pollock scaling behavior varies between paintings and here we describe a few common categories: 1) the scaling plots fail to display scale invariance across any length scales. Figure 3(c) is an example of this behavior. 2) The scaling plots exhibit well-defined D_L behavior but fail to condense onto a well-defined D_D behavior (this commonly results in a forced fit procedure because the free fit produces an L_T value well below L = 1cm). Figure 3(b) is an example of this behavior. A further example is *Tumulte* (1973) painted by Les Automatists (Mukeika et al., 2004). 3) The scaling plots display D = 2 across many length scales, indicative of a 'space-filled' canvas produced by excessive paint deposition. 4) The scaling plots display $D_D = 1$, indicative of overly smooth paint trajectories that lacked "splatter" in the pouring process.

3. Conclusions

We conclude by emphasizing that the results presented in this Letter are part of an on-going research project. Nevertheless, the results obtained to date – based on 35 paint layers extracted from 17 authentic Pollock paintings – demonstrate a 100% success rate in terms of Pollock's paintings matching the 6 fractal criteria presented. This is in contrast to the 100% failure rate of the 37 layers from non-Pollock paintings of known origin – none of these paintings satisfied all 6 criteria. These initial results demonstrate the potential of computers to detect the trademark characteristics of Pollock's patterns and to use fractal analysis as an authenticity tool. The 100% failure rate of the paintings of unknown origin sent to us by private collectors is consistent with expectations - non-Pollock poured paintings are believed to vastly out-number undiscovered real Pollock paintings (for example, in the 17 years between publication of the Pollock Catalogue Raisonné and its supplement (O'Connor and Thaw, 1978; O'Connor, 1995), only six new Pollock paintings were authenticated). In future work, the fractal analysis presented here will be particularly effective when combined with the traditional authenticity tools outlined earlier and other fractal analysis techniques that have recently been applied to Pollock's poured paintings (Mukeika et al., 2004). The latter research concentrates on the D_L regime, and includes a multi-fractal spectral analysis (measuring a range of dimensions that build on the 'box-counting' D_L) and also an investigation of the D_L behavior of the fractal edge patterns at the boundaries between the paint and canvas. Future collaborations will also focus on wavelet analysis (Lyu et al., 2004) and pattern connectivity analysis (Martin et al., 2004).

Finally, we note that the impact of fractal analysis as an authenticity tool is not restricted to Pollock's poured works. For abstract artists who painted non-fractal patterns, fractal analysis could be used to detect the trademark characteristics of how their patterns deviate from fractal scale invariance. Furthermore, fractal analysis can be applied to both abstract and figurative paintings. Fractal and other forms of scale analysis have been used by other researchers to investigate artists as diverse as early Chinese figurative painters (Voss, 1998), Vincent Van Gogh (Herik and Postma, 2000) and Pieter Bruegel the Elder (Lyu et al., 2004). The application of fractal analysis isn't restricted to the painted image of an art work - for example, stress fractures are fractal and therefore fractal analysis can be used to investigate the cracks that form in the paint layers of ageing paintings. More generally, we anticipate that fractal analysis will be integrated with other forms of computer-analysis, with the goal of authenticating paintings using a wide spectrum of quantifiable parameters. These parameters will extend beyond the 'form' of the painting to include information relating to color, physical size and materials. In particular, the latter will be collected using an array of scientific tools (which includes X-ray, ultraviolet and infrared radiation techniques, optical and electron-beam microscopy (McCrone, 2001) and forensics techniques such as fingerprint and DNA analysis). Ultimately, art scholars and connoisseurs will be able to combine their knowledge with a data-base of scientific information involving the entire catalog of known paintings by the artist. In this sense, the research in this Letter, along with other projects such as the Rembrandt Research Project (see for example Bruyn et al., 1990) and Authentic (Heingartner, 2004), represent the future direction of authenticity work and signal the growing interplay between art and science.

Acknowledgments:

R.P.T is a Research Corporation Cottrell Scholar. T.P.M. and C.A.M are National Science Foundation IGERT fellows. R.P.T. thanks F.W. O'Connor (author of the Pollock Catalogue Raisonné), J. Coddington (Conservator, Museum of Modern Art, New York), H. Harrison (Director, Pollock-Krasner Study Center) and S. Fletcher (Executive Director, International Foundation for Art Research) for useful discussions during this project's development.

References:

Avnir, D., Biham, O., Lidar, D., Malcai, O., 1998. Is the Geometry of Nature Fractal? Science 279, 39.

Barnsley, M.F., 1992. Fractals Everywhere. Academic Press, San Diego.

Bruyn, J., Haak, B., Levie, S.H., Thiel, P.J.J.v., Wetering, E.v.d., Cook-Radmore, D., (Eds.), 1990. A Corpus of Rembrandt Paintings, Vol. 3. Springer, Amsterdam.

Coddington, J., 1999. No Chaos Damn It, in: Vanredoe, K., Karmel, P. (Eds.), Jackson Pollock: New Approaches. Museum of Modern Art, New York, pp. 100-113.

Gouyet, J.F., 1996. Physics and Fractal Structures. Springer, New York.

Heingartner, D., 2004. A Computer has an Eye for Van Gogh. New York Times, June 13^{th}.

Herik, H.J., Postma, E.O., 2000. The Hand of The Master - An Analysis of the Visual Signature of Painters, in: Kasabov, N. (Eds.), Future Directions for Intelligent Systems and Information Sciences. Springer-Verlag, New York, pp. 129.

Lyu, S., Rockmore, D., Farid, H., 2004. A Digital Technique for Art Authentication. In: Proc. National Academy of Science, Vol. 101, pp. 17006-17010.

Mandelbrot, B.B., 1977. The Fractal Geometry of Nature. W.H. Freeman and Company, New York.

Martin, C.P., Blunt, M.O., Moriarty, P., 2004. Nanoparticle Networks in Silicon: Self-organized or Disorganized. Nanoletters 4, 2389-2392.

McCrone, W.C., 2001. Artful Dodgers: Virtuosos of Art Forgery Meet the Masters of Scientific Detection. The Sciences, 32, January-February edition.

Mukeika, J.R., Cupchik, G.C., Dyer, C.C., 2004. Multifractal Fingerprints in the Visual Arts. Leonardo 37, 1.

Naifeh, S., Smith, G.W., 1989. Jackson Pollock: An American Saga. Clarkson N. Potter Inc., New York.

Namuth, H., 1980. Photographing Pollock, in: Rose, B. (Eds.), Pollock Painting. Agrinde Publications, New York, pp. 1.

O'Connor, F.V., Thaw, E.V., 1978. Jackson Pollock: A Catalogue Raisonné of Paintings, Drawings and Other Works. Yale University Press, New Haven.

O'Connor, F.V., 1995. Supplement One to Jackson Pollock: A Catalogue Raisonné of Paintings, Drawings and Other Works. British Museum Publications Ltd., London.

Potter, J., 1985. To a Violent Grave: An Oral Biography of Jackson Pollock. G.P. Putman and Sons, New York.

Schroeder, M., 1991. Fractals, Chaos, Power Laws. W. H. Freeman and Company, New York.

Shi, X.D., Brenner, M.P., Nagel, S.R., 1994. A Cascade Structure in a Drop Falling From a Faucet. Science 219, 265.

Spenser, R.D., 2004. The Expert versus the Object. Oxford University Press, Oxford.

Taylor, R.P., 1998. Splashdown. New Scientist 2144, 31.

Taylor, R.P., Micolich, A.P., Jonas, D., 1999a. Fractal Analysis of Pollock's Drip Paintings. Nature 399, 422.

Taylor, R.P., Micolich, A.P., Jonas, D., 1999b. Fractal Expressionism: Art, Science and Chaos. Physics World 12, 25.

Taylor, R.P., 2000. Jackson Pollock: Nature, Chaos and Fractals. Masters Thesis of Art Theory, University of New South Wales, Sydney.
Taylor, R.P., 2002. Order in Pollock's Chaos. Scientific American 287, 84.
Taylor, R.P., 2003a. Fractal Expressionism - Where Art Meets Science, in: Casti, J., Karlqvist, A. (Eds.), Art and Complexity. Elsevier Press, Amsterdam, pp. 117.
Taylor, R.P., Micolich, A.P., Jonas, D., 2003b. The Construction of Pollock's Fractal Drip Paintings. Leonardo 35, 203.
Taylor, R.P., 2004. Lévy Flights, in: Scott, A. (Eds.), Encyclopedia of Non-linear Science. Fitzroy-Dearborn, London.
Taylor, R.P., Gatts, S., Boydston, C., manuscript in preparation. Fractal Analysis of Human Motion During Balance Restoration.
Varnedoe, K., 1998. Comet: Jackson Pollock's Life and Work, in: Varnedoe, K., Karmel, P. (Eds.), Jackson Pollock. The Museum of Modern Art, New York, pp. 1.
Voss, R.F., 1998. Local Connected Fractal Dimension Analysis of Early Chinese Landscape Paintings and X-ray Mammograms. Fractal Image Encoding and Analysis, NATO ASI series 159, 279.

Figures:

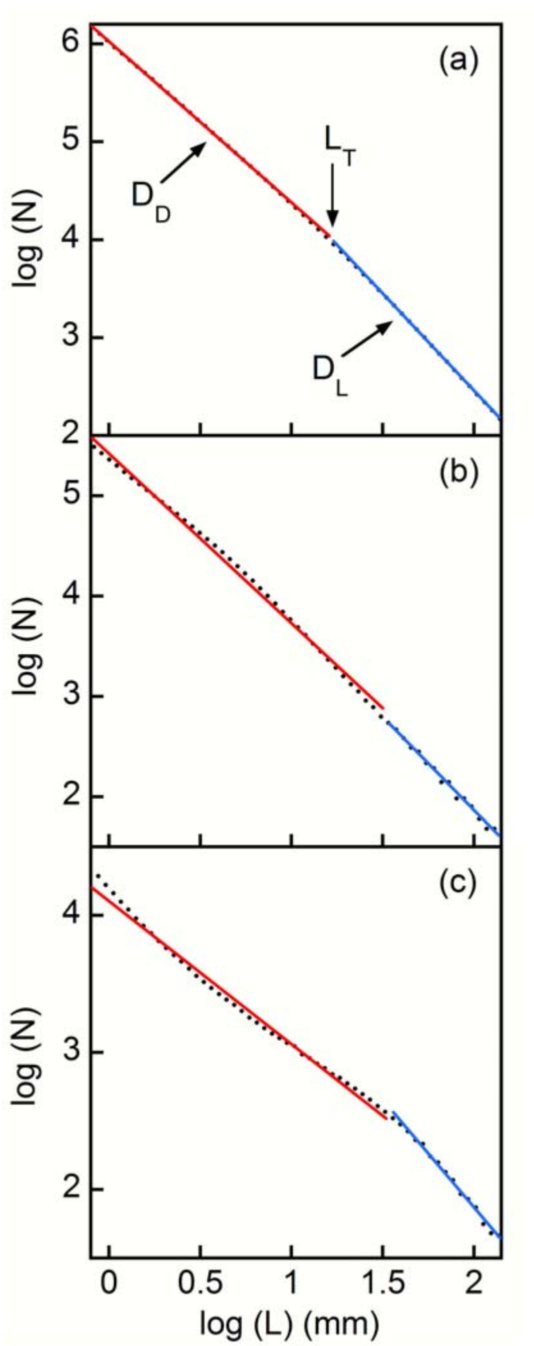
Figure 1

Blue Poles: Number 11, 1952 (enamel and aluminum paint on canvas, 210.4cm by 486.8cm) was painted by Pollock in 1952 (The National Gallery of Australia, Canberra, Australia).

Figure 2

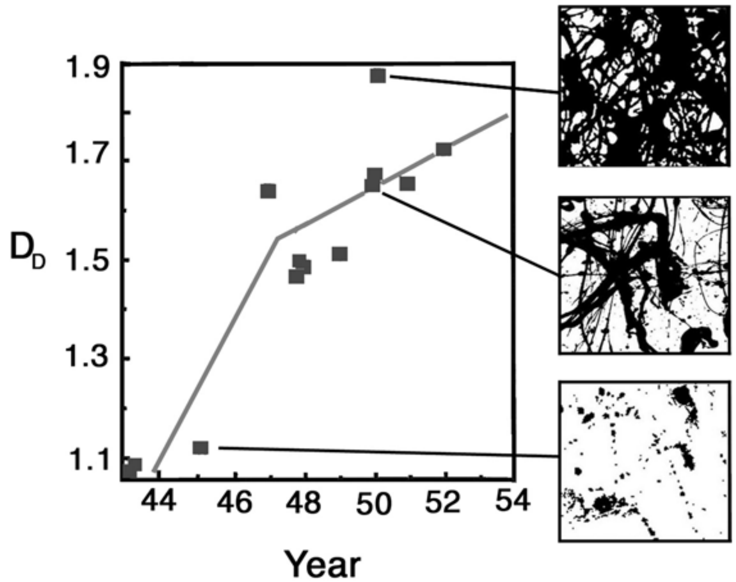
A poured painting of unknown origin (enamel on canvas, 64.0cm by 101.6 cm) submitted by a private collector for fractal analysis.

Figure 3



Box-counting analyses of: (a) the aluminum layer of the painting *Blue Poles: Number 11, 1952* shown in Figure 1, (b) the black layer of a painting generated by an art student, (c) the black layer of the painting of unknown origin shown in Figure 2.

Figure 4



Fractal dimension D_D plotted as a function of the year the pattern was painted by Pollock. The two lines serve as guides to the eye (see text for details). Sections of Pollock's paintings are shown as examples of fractal patterns with different *D* values. Top to bottom: *Untitled*, 1950 (D_D = 1.89), the black layer of *Autumn Rhythm: Number 30, 1950,* 1950 (D_D = 1.66), the black layer of *Untitled*, 1945 (D_D = 1.12).

Figure 5

An example of a poured painting generated by a student (61.6cm by 91.5cm).